JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. C12, PAGES 22,579–22,587, DECEMBER 15, 1993

# A Theoretical Model of Ultraviolet Light Transmission Through Antarctic Sea Ice

D. K. PEROVICH

*U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire*

Much of the region of the Earth most affected by stratospheric ozone depletion is covered by a seasonal or perennial sea ice cover, which is the habitat of a productive and extensive sea ice microbial community. To assess the impact of enhanced incident ultraviolet irradiance on this community, a knowledge of the amount of light transmitted through a sea ice cover is necessary. A two-stream radiative transfer model is used to estimate the penetration of ultraviolet radiation through Antarctic sea ice. Sea ice optical properties were used as proxies to infer scattering and absorption coefficients at ultraviolet wavelengths. Case studies are reported for sea ice in McMurdo Sound and in the Weddell Sea. Values of spectral transmittance are computed as well as integrated transmitted UV-B, UV-A, biologically effective irradiance (BEI), and photosynthetically active radiation (PAR). UV-B light levels under meter-thick ice are a few percent of incident values. The presence of a snow cover results in a large decrease in transmitted ultraviolet. Snow and ice ameliorate the biological impact of enhanced levels of incident ultraviolet radiation by reducing the BEI relative to the PAR.

## INTRODUCTION

The discovery of significant seasonal ozone depletion in the Antarctic and more recently in the Arctic has focused major research efforts on both the causes and the potential effects of this depletion. Considerable progress has been made in understanding the atmospheric and chemical processes responsible for the ozone depletion [*Solomon*, 1988]. Ongoing monitoring efforts are tracking the extent, duration, and severity of the ozone depletion [*Frederick and Snell*, 1988; *Lubin and Frederick*, 1989, 1990; *Krueger et al.*, 1989; *Schoeberl et al.*, 1989; *Stamnes et al.*, 1990; *Frederick and Alberts*, 1991; *Beaglehole and Carter*, 1992]. More recently there have been investigations of the impact of this reduced ozone, primarily concerning the increase in ultraviolet light levels and their impact on biology [*Smith*, 1989; *Lubin et al.*, 1992; *Smith et al.*, 1992*b*].

There is a comprehensive program of measuring ultraviolet irradiance and stratospheric ozone in the Antarctic [*Lubin and Frederick*, 1990; *Lubin et al.*, 1992]. These observations have assisted in assessing the relationship between ozone depletion and ultraviolet radiation and in the development of detailed models of ozone impact on atmospheric radiative transfer at ultraviolet wavelengths [*Frederick and Lubin*, 1988; *Lubin et al.*, 1989; *Tsay and Stamnes*, 1992; *Smith et al.*, 1992*a*; *Madronich*, 1992]. Through these measurements and models, an understanding of the impact of changes in ozone on ultraviolet light levels at the surface has been developed. Ozone depletion results in a substantial increase in light levels from 280 to 320 nm but has little effect beyond 320 nm. The spectral region from 280 to 320 nm is referred to as the UV-B, that from 320 to 400 nm is called the UV-A, and that from 400 to 700 nm is considered visible, or photosynthetically active, radiation (PAR).

Because of the biological abundance of the Antarctic seas, a primary concern is that enhanced levels of ultraviolet radiation will have a deleterious impact on the marine biota [*Smith*, 1989]. A recent comprehensive field program [*Smith et al.*, 1992*b*] examined the impact on photosynthesis in the water column of the marginal ice zone of the Bellingshausen Sea. The authors of that study determined that ultraviolet light penetrated the water column to ecologically important depths and that enhanced levels of UV-B were associated with 6–12% decreases in primary productivity.

Much of the region of the Earth affected by stratospheric ozone depletion is covered by a seasonal, or in some cases perennial, sea ice cover, which is the habitat of a productive and extensive sea ice microbial community [*Palmisano and Sullivan*, 1983; *Garrison et al.*, 1986]. The presence of a sea ice cover further complicates assessing the impact of enhanced ultraviolet levels on the marine biota. To date, there have been few studies of the interaction of ultraviolet radiation with a sea ice cover. *Trodahl and Buckley* [1990] measured ultraviolet transmittance through snow-free, 1.7-m-thick sea ice at McMurdo Sound from October through November 1989. They found maximum UV-B transmittances of 1–2% in October that decreases by an order of magnitude in early November as the surface layer of the ice drains, making it more turbid. This was in agreement with theoretical predictions they generated that assume that ultraviolet absorption coefficients for ice are similar to values for water [*Trodahl and Buckley*, 1989].

In this paper a two-stream radiative transfer model [*Perovich*, 1990] is modified for use at ultraviolet wavelengths and then used to estimate the penetration of ultraviolet radiation through Antarctic sea ice. Ultraviolet extinction and scattering coefficients for representative snow and ice types are presented. Factors affecting the transmission of ultraviolet radiation, such as snow depth and ice thickness, are investigated, and case studies for sea ice in McMurdo Sound and in the Weddell Sea are examined. The focus of the calculations is on estimating spectral ultraviolet transmittance through the ice cover, though wavelength-integrated measures including transmitted UV-A, UV-B, and biologically effective irradiance (BEI) are also computed. Ultraviolet transmittances are also compared to those computed for visible wavelengths.



Paper number 93JC02563.

## THE MODEL

### *Two-Stream Formulation*

A two-stream, multilayer radiative transfer model, similar to the visible and near-infrared model of *Perovich* [1990], is used to compute upwelling and downwelling irradiances from 280 to 400 nm. This formulation was selected for three reasons: it is computationally fast and simple, it can exploit the existing database of sea ice optical properties, and only a qualitative description of the ice conditions is needed [*Perovich*, 1990]. The two streams refer to the downwelling ($F_\downarrow$) and upwelling ($F_\uparrow$) irradiances in the medium. The ice cover is assumed to be plane parallel, consisting of homogeneous layers of finite thickness in $Z$ and infinite in extent in $X$ and $Y$. The optical properties of each layer are defined by wavelength-dependent scattering ($r_\lambda$) and extinction ($K_\lambda$) coefficients, where $\lambda$ refers to wavelength. The downwelling and upwelling irradiances are governed by coupled first-order differential equations of the form

$$dF_\downarrow(z, \lambda) = -k_\lambda F_\downarrow(z, \lambda) - r_\lambda F_\downarrow(z, \lambda) + r_\lambda F_\uparrow(z, \lambda) \tag{1}$$

$$dF_\uparrow(z, \lambda) = k_\lambda F_\uparrow(z, \lambda) - r_\lambda F_\downarrow(z, \lambda) + r_\lambda F_\uparrow(z, \lambda) \tag{2}$$

where the left-hand sides of the equations represent changes in the downwelling or upwelling, and the right-hand sides include losses due to absorption and both losses and gains due to scattering. Here, $k_\lambda$ is the spectral absorption coefficient, and $z$ is the depth within the medium. The extinction coefficient combines the effects of both scattering and absorption and has the form $K_\lambda = (k_\lambda^2 + 2k_\lambda r_\lambda)^{0.5}$. Equations (1) and (2), along with surface and bottom boundary conditions and continuity at the interface between layers, form a system of equations which are solved to compute $F_\downarrow(z, \lambda)$ and $F_\uparrow(z, \lambda)$.

Two quantities of particular concern are the spectral albedo and the spectral transmittance. The spectral albedo ($\alpha_\lambda$) is the fraction of the incident irradiance that is reflected:

$$\alpha_\lambda = \frac{R_0 F_0(\lambda) + F_\uparrow(0, \lambda)}{F_0(\lambda)}$$

and the transmittance ($T_\lambda$) is the fraction of the incident irradiance that is transmitted:

$$T_\lambda = \frac{F_\downarrow(H, \lambda)}{F_0(\lambda)}$$

where $F_0(\lambda)$ is the incident spectral irradiance, $R_0$ is the specular reflection from the surface, and $H$ is the total thickness of the ice cover. Bulk values of a property are computed by integrating spectral values over wavelength using

$$P_B = \frac{\int P(\lambda) F_0(\lambda)\, d\lambda}{\int F_0(\lambda)\, d\lambda}$$

where $P$ is the property of interest.

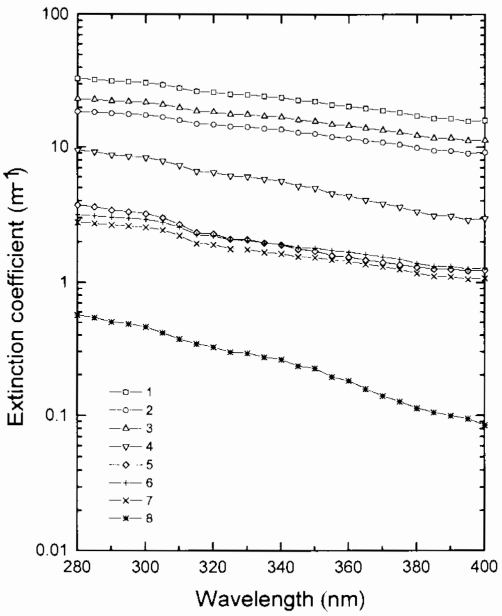


Fig. 1. Ultraviolet extinction coefficients estimated from visible values: 1, dry snow; 2, wet snow; 3, ice colder than the eutectic point; 4, surface scattering layer of white ice; 5, interior portion of white ice; 6, cold blue ice; 7, melting blue ice; 8, bubble-free fresh ice.

The input parameters to the model are spectral scattering and extinction coefficients for different snow and ice types, incident spectral irradiances, and biological action spectra. The model calculates spectral albedos and transmittances and wavelength-integrated values of incident, reflected, and transmitted UV-A and UV-B radiation plus the biologically effective irradiance.

### *Sea Ice Optical Parameters*

The critical input parameters for the model are spectral scattering and extinction coefficients for different snow and sea ice types. Such quantities have not been measured for either Arctic or Antarctic sea ice at ultraviolet wavelengths. However, *Perovich and Govoni* [1991] measured spectral absorption coefficients for pure bubble-free ice from 250 to 400 nm and found that values were comparable to those determined for visible wavelengths from 580 to 720 nm. In addition, since the scattering inhomogeneities in sea ice are much larger than ultraviolet or visible wavelengths, scattering properties are assumed to be essentially constant with wavelength [*Bohren and Huffman*, 1983; *Grenfell*, 1983], implying that ultraviolet scattering coefficients ($r_\lambda$) are equal to visible values. Because of this, it is possible to use the relatively large database on the optical properties of sea ice at visible wavelengths as a first-order proxy for the ultraviolet properties. Extinction coefficients were generated for various snow and ice types using the visible to ultraviolet wavelength-mapping technique suggested by *Perovich and Govoni* [1991] and requiring that spectral extinction coefficients be continuous at 400 nm. For highly scattering types it was necessary to shift the mapped extinction coefficients downward to satisfy the continuity constraint. Figure 1 summarizes ultraviolet extinction coefficients obtained from visible results for eight snow and ice types [*Grenfell and*

*Maykut*, 1977; *Grenfell*, 1979; *Grenfell and Perovich*, 1981; *Perovich and Grenfell*, 1981; *Perovich*, 1990]: (1) cold dry snow ($r_\lambda$ = 800 $m^{-1}$), (2) melting wet snow ($r_\lambda$ = 160), (3) ice colder than the eutectic temperature ($r_\lambda$ = 160), (4) surface scattering layer of white ice ($r_\lambda$ = 120), (5) interior of white ice ($r_\lambda$ = 2.5), (6) cold blue ice ($r_\lambda$ = 1.8), (7) melting blue ice ($r_\lambda$ = 1.2), and (8) bubble-free fresh ice ($r_\lambda$ = 0.0). Figure 1 shows that extinction coefficients increase with decreasing wavelength and that there are large differences in extinction coefficient between different ice types.

The data reported in Figure 1 are derived from observations of Arctic sea ice. There is reason to believe that these results are applicable to Antarctic sea ice. The physical properties (e.g., ice salinity, brine volume, and structure) of shore-fast ice in the Antarctic, such as that found in McMurdo Sound, are similar to those of ice in the Arctic, so the optical properties are also expected to be similar. Ice grown under more dynamic conditions, such as in the Weddell Sea, is known to differ structurally from Arctic pack ice, having a large frazil ice component [*Gow and Tucker*, 1990]. An analysis of light transmittance data from work by *Govoni et al.* [1990] indicates that Weddell Sea frazil ice has extinction coefficients comparable to those of the interior of Arctic white ice (Figure 1, curve 5).

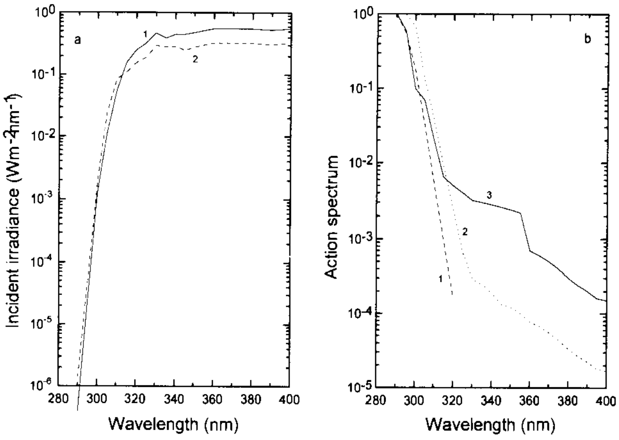


Fig. 2. Radiative transfer model input parameters: (*a*) ultraviolet incident irradiance at Palmer Station on December 14 (curve 1) and October 19 (curve 2), 1988 [*Lubin and Frederick*, 1989]; (*b*) selected action spectra. 1, DNA [*Setlow*, 1974]; 2, erythemal effects [*McKenzie et al.*, 1991]; 3, photoinhibition [*Mitchell*, 1990].

### *Incident Irradiance*

While some parameters, such as spectral albedos and transmittances, are independent of the incident spectral irradiance, there are others that do depend on $F_0(\lambda)$. In particular, information on the spectral distribution of incident irradiance is needed to compute wavelength-integrated values of transmitted UV-A, UV-B, and BEI. These bulk values are particularly important when investigating biological consequences, since in many species UV-A acts as a photoregulator for UV-B; thus if UV-B increases without a corresponding increase in UV-A, the species may be unprotected. *Smith et al.* [1992*b*] found that this was the simplest scenario to explain their findings of reduced water column productivity with enhanced levels of UV-B. The amount of PAR is also important, since it ameliorates the damage caused by the UV-B [*Smith et al.*, 1992*b*].

Spectral incident irradiances can vary greatly, depending on solar elevation angle and cloud conditions as well as total column ozone. The model is designed so that it is easy to add additional incident irradiance spectra. Figure 2*a* shows sample incident spectra measured from 295 to 350 nm at Palmer Station on December 14, 1988 (Figure 2*a*, curve 1), and October 19, 1988 (Figure 2*a*, curve 2), by *Lubin and Frederick* [1989]. The incident irradiances were extrapolated from 295 to 280 nm by assuming a constant exponential decrease in irradiance and were extended beyond 350 nm using the spectral shape of the observations of *Smith et al.* [1992*b*]. October 19 was during the period of maximum ozone depletion, when incident irradiances from 295 to 315 nm reached their maximum values.

### *Biologically Effective Irradiance*

A parameter of interest when assessing the impact of enhanced ultraviolet light levels on marine organisms is the biologically effective irradiance ($B_E$), defined as the convolution of the appropriate action spectrum with the solar spectral irradiance, or

$$B_E(z) = \int A(\lambda)F(z, \lambda)\, d\lambda$$

where $A(\lambda)$ is the biological weighting or action spectrum. The action spectrum is a wavelength-dependent function which describes the relative impact of ultraviolet radiation on a given life process for a given organism [*Frederick and Snell*, 1988; *Lubin et al.*, 1992; *Madronich*, 1992]. The appropriate action spectra for various processes and organisms are not well understood, and this is an area of ongoing research [*Smith*, 1989]. Selected action spectra for DNA damage [*Setlow*, 1974; *Lubin et al.*, 1992], photoinhibition [*Mitchell*, 1990; *Lubin et al.*, 1992], and erythemal effects [*McKenzie et al.*, 1991] were chosen to illustrate the potential impact of a sea ice cover on the biologically effective irradiance (Figure 2*b*). In each of these three cases, the action spectrum drops off abruptly as the wavelength increases, decreasing by more than 2 orders of magnitude from 290 to 320 nm and thus reaffirming the importance of UV-B light levels on biological processes.

While the exact form of the action spectrum is a topic of current investigation, it is known that the spectrum is weighted heavily toward the UV-B. This is confirmed by previous experimental studies [*Calkins*, 1982; *Smith*, 1989] that indicated that enhanced levels of UV-B result in reduced algal productivity and cause damage to other marine organisms. *Smith et al.* [1992*b*] studied the photoreactivation and photoprotective strategies of phytoplankton and found evidence that the cells used UV-A levels to regulate their response to UV-B. While UV-B radiation is damaging to the organism, PAR is beneficial. This argues that what is biologically significant is not just the absolute level of ultraviolet radiation but the relative amounts of UV-A, UV-B, and PAR [*Smith et al.*, 1992*b*]. Of particular importance is the ratio of the biologically effective irradiance to the photosynthetically active radiation, or in other words, the ratio of the damaging to the beneficial radiation.

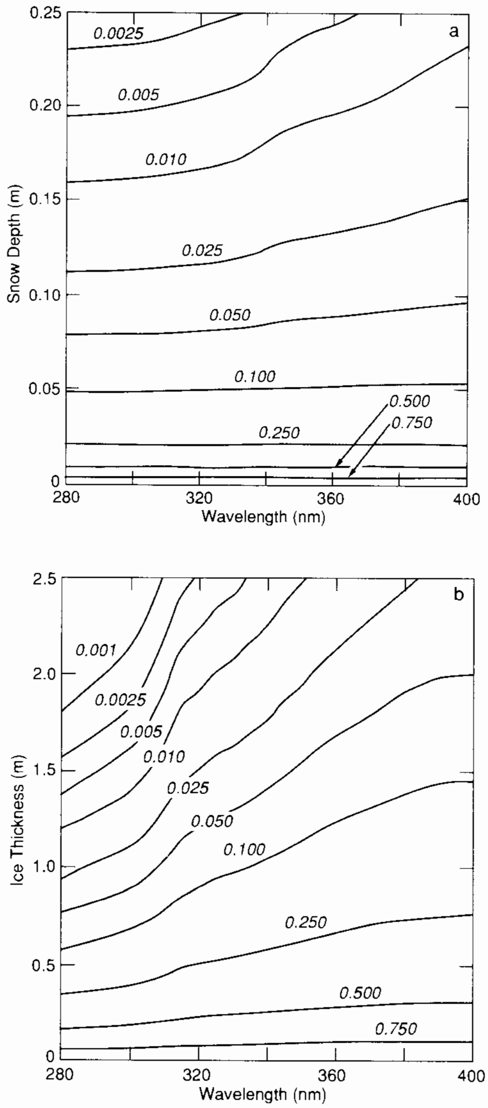


Fig. 3. Isopleths of constant transmittance from 280 to 400 nm for (*a*) wet snow depths from 0.0 to 0.25 m and (*b*) ice thickness (white-ice interior) from 0.0 to 2.5 m.

### *Model Evaluation*

Evaluating the suitability of the model and the derived optical constants is limited by a scarcity of field observations of the reflection and transmission of ultraviolet light by sea ice. The model was applied to two cases for which there is observational evidence; albedos of bare and snow-covered sea ice (D. K. Perovich, unpublished data, 1993) and light transmission through McMurdo Sound sea ice [*Trodahl and Buckley*, 1990]. There was excellent agreement between observation and theory for the bare-ice albedos. Observed albedos for snow-covered ice were slightly lower than predicted owing to the presence of contaminants in the snow, which the model does not consider. For the transmission data there was good agreement in the UV-B between observation and theory for ice with a drained surface layer. At longer wavelengths, near 400 nm, observed transmittances were smaller than calculated owing to absorption by biological material, which is not included in the model. Because of the limited amount of field data and the extrapolation necessary to obtain the optical constants, it is important to consider the results of this model only as an estimate of the reflection and transmission of ultraviolet light by sea ice.

## RESULTS

The radiative transfer model will now be used to examine the interaction of ultraviolet light with Antarctic sea ice. First, the influence of ice thickness and snow depth on ultraviolet transmittance is investigated. Examples from McMurdo Sound and the Weddell Sea are then presented to give an overview of representative Antarctic ice conditions. The McMurdo Sound case focuses on temporal changes in ultraviolet transmittance of shore-fast ice, while the Weddell Sea case examines how spatial variability in ice physical properties affects ultraviolet transmittance. In addition, the biological impact of enhanced ultraviolet light levels is studied by examining the effect of the ice cover on the ratio of the biological effective irradiance to the photosynthetically active radiation.

### *Snow Depth and Ice Thickness*

We begin with a survey of the impact of snow depth and ice thickness on transmitted ultraviolet light levels. Isopleths of spectral transmittance from 280 to 400 nm are plotted as a function of thickness for wet (flooded) snow (Figure 3*a*) and white-ice interior (Figure 3*b*). These conditions are representative of much of the Weddell Sea, where a large portion of the snow cover is infiltrated by sea water in the spring and the dynamically grown ice has optical properties similar to those of Arctic white-ice interior. The plots show that the presence of a snow or ice cover can significantly reduce ultraviolet light levels. Attenuation was roughly an order of magnitude greater in wet, flooded snow than in frazil ice. For example, it took approximately 0.1 m of wet snow or 1.0 m of ice to reduce UV-B light levels to 2.5% of incident light. Thus ultraviolet transmittances are very sensitive to snow depth. For comparison, a similar reduction in the open ocean would require a water depth on the order of 30 m [*Smith and Baker*, 1981; *Smith et al.*, 1992*b*]. Both wet snow and frazil ice exhibited increasing attenuation at longer wavelengths. The wavelength dependence was more pronounced as the layer grew thicker and was stronger for ice than snow.

### *McMurdo Sound*

Sea ice in McMurdo Sound is shore-fast, first-year ice. Conditions here are representative of much of the shore-fast, first-year ice found around the periphery of the Antarctic continent. The ice is composed predominantly of columnar crystals, is structurally similar to Arctic sea ice, and is approximately 2 m thick at the end of the growth season in December. Snow covers much of the ice; depths range from 0.0 to 0.6 m and average about 0.15 m. There are, however, substantial areas of bare ice where katabatic winds have removed the snow cover. During the melt season, the ice deteriorates internally without any surface melt features [*Gow et al.*, 1982; *Trodahl and Buckley*, 1989]. As the ice warms, brine drains from the surface layer. This change from liquid-filled brine pockets to vapor-filled air bubbles increases the turbidity of the upper portion of the ice.

Figure 4 shows calculated estimates of the changes in spectral albedos and transmittances associated with the physical evolution of sea ice in McMurdo Sound. The initial conditions are 2-m-thick cold ice with a 0.2-m-thick snow cover [*Gow et al.*, 1982; *Trodahl and Buckley*, 1990]. At this stage, ultraviolet albedos are nearly 1, and transmittances are quite small, ranging from $10^{-7}$ at 280 nm to $10^{-4}$ at 400 nm. As the snow begins to thin (curves 2 and 3) through sublimation [*Andreas and Ackley*, 1981], albedos change very little, though transmittances increase across the spectrum by 1 to 2 orders of magnitude. The minimum albedo and maximum transmittance occur for bare, cold ice (curve 4). As the ice begins to warm, brine drains from the surface layer, increasing the turbidity of the ice (curve 5). This results in an increase in albedo and a decrease in transmittance. As *Trodahl and Buckley* [1989, 1990] point out, the timing of ozone depletion in relation to the evolution of ice conditions is critical. The impact of a depleted-ozone-induced high level of ultraviolet incident irradiance will be greatest if it occurs during the period of maximum transmittance, when the ice is snow-free but surface brine drainage has not yet occurred.

### *Weddell Sea*

Ice conditions in the Weddell Sea are quite different from those for the shore-fast ice at McMurdo. Weddell Sea ice usually forms under very dynamic conditions and has a greater proportion of frazil than that found in McMurdo Sound or Arctic pack ice [*Gow et al.*, 1987; *Wadhams et al.*, 1987]. Ice in this region is predominantly first-year ice, with typical thicknesses ranging from 0.5 to 1.0 m [*Wadhams et al.*, 1987]. There are significant amounts of flooded ice, and much of the snow cover is infiltrated by sea water in the spring when the ozone depletion is greatest [*Lange and Eicken*, 1991].

*Lange and Eicken* [1991] conducted a detailed survey of ice conditions in the northwest Weddell Sea. They found that the ice in this region could be classified into four categories: strongly deformed first-year ice, first-year ice, multiyear ice, and strongly deformed multiyear ice. The undeformed first-year ice case was selected for analysis, since the ice thicknesses and snow depths are representative of a large portion of the Weddell Sea [*Gow et al.*, 1987; *Wadhams et al.*, 1987]. Figure 5*a* shows a 100-m transect of ice thickness and snow depth for undeformed first-year ice measured during October 1988 [*Lange and Eicken*, 1991]. Ice thicknesses ranged from 0.2 to 1.2 m, and snow depths varied from 0.0 to 0.2 m. Thicknesses sampled every meter were input to the radiative transfer model to compute spectral transmittances and integrated transmitted UV-B. Optical constants for wet snow and for white-ice interior were used in the simulation.

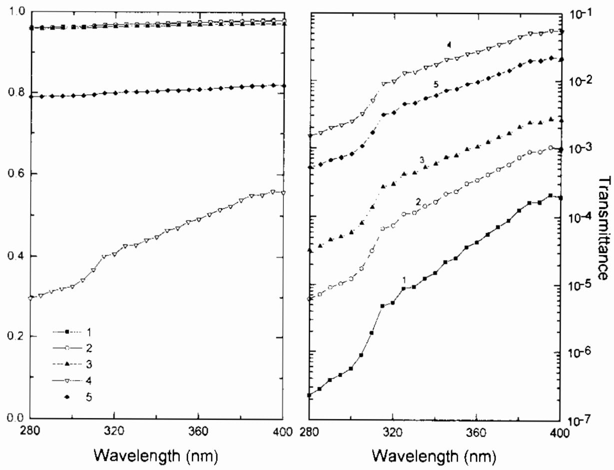


Fig. 4. Simulation of the evolution of ultraviolet albedos and transmittances for McMurdo Sound sea ice: 1, 2.0-m-thick cold ice covered by 0.2-m-thick cold, dry snow; 2, 2.0-m-thick cold ice covered by 0.1-m-thick cold, dry snow; 3, 2.0-m-thick cold ice covered by 0.05-m-thick cold, dry snow; 4, 2.0-m-thick bare, cold ice; 5, 2.0-m-thick warm, melting ice with a drained surface layer. The values of integrated UV-B transmittance for these five cases are (curve 1) 0.0000035, (curve 2) 0.000054, (curve 3) 0.00022, (curve 4) 0.0075, and (curve 5) 0.0026.

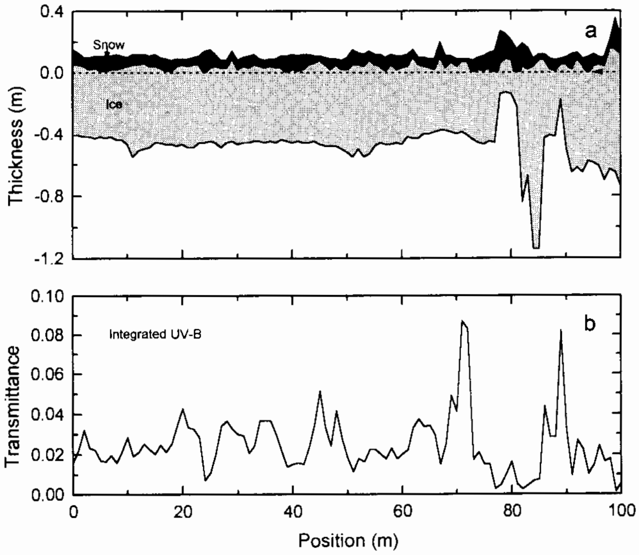


Fig. 5. (*a*) Ice thickness and snow depth along a 100-m-long transect of first-year ice in the Weddell Sea [*Lange and Eicken*, 1991]. (*b*) The corresponding profile of transmitted integrated UV-B.

UV-B transmittances (Figure 5*b*) ranged from 0.0015 to 0.09, with a mean value of 0.025 and a standard deviation of 0.015. As was the case for the McMurdo data, the effect of snow in reducing transmitted UV-B is evident. For example, sharp decreases in UV-B at 25, 40, and 77 m are all associated with increases in snow depth to more than 0.10 m. Because of thinner ice and less snow, transmittances are in general higher than those calculated for McMurdo Sound.

Spectral transmittances along the transect are plotted in Figure 6. At all sites there is a general trend toward increased transmittance as wavelength increases from 280 to 400 nm. Mean transmittances for the transect range from 0.012 at 280 nm to 0.052 at 400 nm. As the plot indicates, there is considerable spatial variability in transmittance. For example, values at 280 nm range from 0.0003 to 0.059, while values at 400 nm range from 0.0092 to 0.15. Again, large spectral transmittances are typically associated with thin snow covers. Smaller spectral transmittances are found under deformed ice, in part because of its greater thickness and in part because the deformed surface tends to collect more snow.

### *Biological Effects*

The focus of the previous sections has been on estimating ultraviolet light levels under sea ice. The more important and

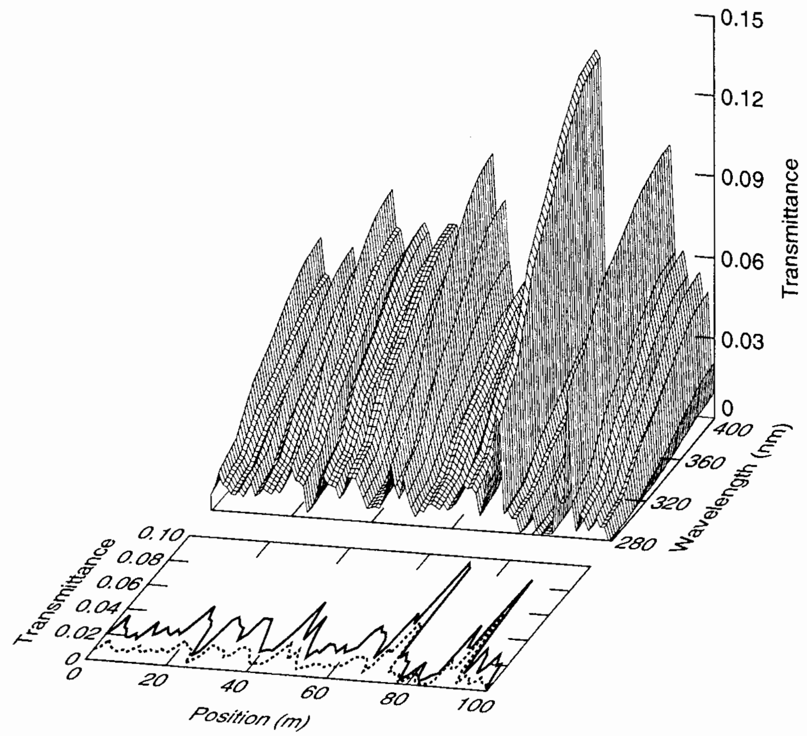


Fig. 6. Spectral transmittances from 280 to 400 nm along the transect plotted in Figure 5*a*. UV-B transmittances at 280 and 320 nm are also plotted separately for clarity.

more complicated question concerns the biological impact of these light levels. A precise answer to that question requires a detailed knowledge of the evolution of the spectral incident irradiance and of the pertinent action spectra and is well beyond the scope of this work. However, it is possible to apply the model to obtain some broad insights and in particular to examine the relative amounts of harmful (BEI) and beneficial (PAR) radiation transmitted through snow and ice.

Because of the potential biological importance of the BEI

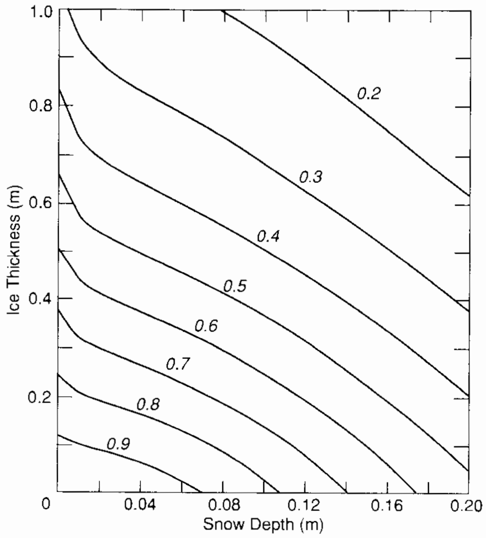


Fig. 7. Isopleths of BEI/PAR ratio plotted as a function of snow depth and ice thickness. The ratios were normalized by the surface value of BEI/PAR.

to PAR ratio, I investigated the variability of this ratio as a function of snow depth and ice thickness. Plotted in Figure 7 are isopleths of the transmitted BEI to PAR ratio for wet snow depths ranging from 0.0 to 0.2 m, white-ice interior (representative of Weddell Sea ice) thicknesses from 0.0 to 1.0 m, an ozone-depleted incident irradiance (Figure 2*a*, curve 2), and a DNA action spectrum (Figure 2*b*, curve 1). Transmitted PAR was calculated using the visible radiative transfer model of *Perovich* [1990]. Transmitted BEI/PAR ratios were normalized by the incident value of BEI/PAR. Not only does the presence of snow or ice reduce UV-B light levels, but it also reduces the ratio of BEI to PAR. As the snow gets deeper and the ice gets thicker, the BEI/PAR ratio decreases from 1.0 at the surface to 0.2 under 1.0 m of ice covered by 0.2 m of snow. This implies that the ice cover could possibly give added protection to under-ice organisms. For typical Weddell Sea conditions of 0.5-m-thick ice and 0.1-m-thick snow, the transmitted BEI/PAR ratio is less than half of the surface value. This reduction is a direct result of extinction coefficients being larger at UV-B wavelengths than at visible wavelengths. Thus UV-B light is attenuated faster than the visible light, causing the BEI to decrease faster than the PAR.

Though our focus has been on transmitted ultraviolet irradiance, enhanced levels of ultraviolet light at the surface make sunburn a concern. In this case the ice cover exacerbates the problem rather than ameliorating it. The erythemal action spectrum (Figure 2*b*, curve 2) shows a maximum sensitivity to UV-B radiation. If even a thin snow cover is present, UV-B albedos are quite large, ranging from 0.9 to nearly 1.0. During the period of minimum ozone and maximum incident ultraviolet, most of the ice is snow covered. While bare-ice albedos are less (0.3 to 0.8), significant

TABLE 1. Summary of Ultraviolet Transmittance Statistics for Antarctic Sea Ice

| | | | | Weddell Sea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | McMurdo Sound | | | First-Year Ice | | | Multiyear Ice | | |
| Summary Statistic | UV-A | UV-B | BEI | UV-A | UV-B | BEI | UV-A | UV-B | BEI |
| Mean | 0.0092 | 0.0018 | 0.0009 | 0.042 | 0.025 | 0.019 | 0.0028 | 0.0011 | 0.0007 |
| Median | 0.0071 | 0.0013 | 0.0006 | 0.039 | 0.022 | 0.017 | 0.0010 | 0.0001 | 0.0000 |
| Standard deviation | 0.0091 | 0.0020 | 0.0010 | 0.020 | 0.015 | 0.012 | 0.0176 | 0.0095 | 0.0068 |
| Minimum | 3.5*E*-0.5* | 7.1*E*-07 | 2.3*E*-07 | 5.7*E*-03 | 1.5*E*-03 | 8.7*E*-04 | 8.4*E*-06 | 4.7*E*-08 | 1.1*E*-08 |
| Maximum | 0.028 | 0.006 | 0.003 | 0.128 | 0.087 | 0.073 | 0.178 | 0.095 | 0.069 |
| | | | | *Frequency Distribution, %* | | | | | |
| Transmittance interval | | | | | | | | | |
| 0.0 to 0.00001 | 0 | 8 | 13 | 0 | 0 | 0 | 3 | 15 | 18 |
| 0.00001 to 0.0001 | 8 | 21 | 17 | 0 | 0 | 0 | 9 | 35 | 62 |
| 0.0001 to 0.0005 | 13 | 4 | 17 | 0 | 0 | 0 | 6 | 49 | 19 |
| 0.0005 to 0.001 | 8 | 13 | 25 | 0 | 0 | 1 | 32 | 1 | 0 |
| 0.001 to 0.005 | 13 | 42 | 29 | 0 | 5 | 8 | 50 | 0 | 0 |
| 0.005 to 0.01 | 21 | 13 | 0 | 3 | 6 | 6 | 0 | 0 | 0 |
| 0.01 to 0.05 | 38 | 0 | 0 | 70 | 85 | 82 | 0 | 0 | 0 |
| 0.05 to 0.1 | 0 | 0 | 0 | 24 | 4 | 3 | 0 | 1 | 1 |
| 0.1 to 0.25 | 0 | 0 | 0 | 3 | 0 | 0 | 1 | 0 | 0 |

Statistics estimate large-scale transmitted values of UV-A, UV-B, and BEI for McMurdo Sound sea ice [*Gow et al.*, 1987] and first-year and multiyear sea ice in the Weddell Sea [*Lange and Eicken*, 1991]. Transmitted BEI values are relative to incident levels. Mean values of snow depth ($h_s$) and ice thickness ($H_i$) are $h_s$ = 0.13 m and $H_i$ = 2.0 m for ice in McMurdo Sound, $h_s$ = 0.08 m and $H_i$ = 0.52 m for first-year ice in the Weddell Sea, and $h_s$ = 0.34 m and $H_i$ = 1.30 m for multiyear ice in the Weddell Sea.

*Read 3.5*E*-0.5 as $3.5 \times 10^{-5}$.

amounts of UV-B are still reflected. Coupling a high-albedo environment with enhanced incident UV-B poses a significant risk of erythemal damage.

### *Large-Scale Statistics*

The previous examples have illustrated that there is considerable spatial and temporal variability in ultraviolet light levels under a sea ice cover. Let us now try to estimate some of the large-scale statistics of ultraviolet light transmission through the Antarctic sea ice. We shall consider three cases; shore-fast, first-year ice in McMurdo Sound; first-year ice in the Weddell Sea; and multiyear ice in the Weddell Sea. Ice property data from A. J. Gow (24 sites; personal communication, 1993) are used for McMurdo Sound, while observations by *Lange and Eicken* [1991] are used to represent first-year and multiyear ice in the Weddell Sea (100 sites each). The mean values of snow depth ($h_s$) and ice thickness ($H_i$) for these three cases are $h_s$ = 0.13 m and $H_i$ = 2.0 m for ice in McMurdo Sound, $h_s$ = 0.08 m and $H_i$ = 0.52 m for first-year ice in the Weddell Sea, and $h_s$ = 0.34 m and $H_i$ = 1.30 m for multiyear ice in the Weddell Sea. Following the methodology of *Perovich* [1990], ultraviolet transmittance statistics are determined using distributions of snow depths and ice thicknesses rather than just estimating transmittance from mean values.

Table 1 summarizes the statistics of UV-A and UV-B transmittance and the transmitted BEI for these three cases. These wavelength-integrated measures were computed using curve 2 from Figure 2*a* as the incident spectrum. While selecting a different incident spectrum would cause some change in the results, there would be little relative change among the three cases. Mean levels of transmitted UV-A, UV-B, and BEI are significantly higher for the relatively thin first-year ice in the Weddell Sea than for the other two cases. Transmittances were lowest for Weddell Sea multiyear ice, owing mainly to larger snow depths than at McMurdo.

When considering the biological impact of transmitted ultraviolet, it is necessary to consider the transmittance distribution as well as the mean value. For example, a substantial fraction of an area may have damaging levels of ultraviolet transmittance even though the mean level for the area is below the harmful threshold. Also recorded in Table 1 are the UV-A, UV-B, and BEI transmittance distributions for the three cases, showing the percentages of the area where transmittances are at certain levels. The frequency distributions reaffirm that the transmittance through first-year ice in the Weddell Sea was much greater than through multiyear ice or first-year ice in McMurdo Sound. UV-B transmittances are above 0.01 under nearly 90% of the first-year ice in the Weddell Sea. For the McMurdo Sound and Weddell Sea multiyear cases, UV-B transmittances are always less than 0.01 and are usually less than 0.005. Similarly, transmitted BEI levels are typically between 0.01 and 0.05 of incident values for first-year ice in the Weddell Sea and less than 0.005 for the other two cases.

## CONCLUSIONS

The results presented in this paper indicate that the presence of a sea ice cover causes a significant reduction in ultraviolet light levels, a reduction that is even greater if the ice is snow-covered. For example, a 0.1-m-thick snow cover reduces ultraviolet light levels by almost 2 orders of magnitude. Attenuation of UV-B radiation was found to be greater than that of UV-A or visible light. Thus not only do snow and ice reduce the overall amount of ultraviolet, but they may also temper the biological impact by reducing the BEI relative to the PAR.

The intent of this study is to provide a theoretical framework for modeling the interaction of ultraviolet light with sea ice and to calculate estimates of ultraviolet transmittance for representative Antarctic ice conditions. This work is viewed only as a first step, and there is much that needs to be done to gain an improved understanding of radiative transfer in sea ice at ultraviolet wavelengths. Of primary importance are observations of the reflection and transmission of ultraviolet light by sea ice and snow, from which extinction and scattering coefficients could be computed. This would enable the extinction and scattering coefficients used in this study to be verified and improved. With detailed time series of incident ultraviolet spectra becoming available, theoretical studies of long-term seasonal variations of ultraviolet light levels under the ice could be performed. Another area of interest is determining ultraviolet light levels in the upper portion of the ice near the waterline, where vigorous biological activity has been reported (S. F. Ackley, personal communication, 1993). Other refinements to the model, such as incorporating the effects of biology on ultraviolet transmittance, would be valuable. At present, light absorption by the biota is not included in the model, so potential reductions in ultraviolet levels due to biology cannot be evaluated.

While results from this study show that ultraviolet light levels under snow and ice are much less than incident values, the biological ramifications of this are far from evident. For example, even though ultraviolet light levels under an ice cover are low, the ice biota may be shade adapted, with minimal defenses against UV-B. It is necessary to couple results from a radiative transfer model with an understanding of the impact on biological processes.

*Acknowledgments.* The author thanks A. J. Gow and H. Eicken for generously supplying ice property information for McMurdo Sound and the Weddell Sea. This work was funded by Office of Naval Research contract N0001492MP24006, Department of the Army Project 4A161102AT24, and CRREL In-House Laboratory Independent Research funds.

## REFERENCES

Andreas, E. L., and S. F. Ackley, On the differences in ablation seasons of the Arctic and Antarctic sea ice, *J. Atmos. Sci.*, *39*, 440–447, 1981.

Beaglehole, D., and G. G. Carter, Antarctic skies, 1, Diurnal variations of the sky irradiance and UV effects of the ozone hole, spring 1990, *J. Geophys. Res.*, *97*, 2589–2596, 1992.

Bohren, C. F., and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, 530 pp., Wiley, New York, 1983.

Buckley, R. G., and H. J. Trodahl, Radiation risk, *Nature*, *346*, 24, 1990.

Calkins, J., *The Role of Solar Ultraviolet Radiation in Marine Ecosystems*, 724 pp., Plenum, New York, 1982.

Cullen, J. J., P. J. Neale, and M. P. Lesser, Biological weighting function for the inhibition of phytoplankton photosynthesis by ultraviolet radiation, *Science*, *258*, 646–650, 1992.

Frederick, J. E., and A. D. Alberts, Prolonged enhancement in surface ultraviolet radiation during the Antarctic spring of 1990, *Geophys. Res. Lett.*, *18*, 1869–1871, 1991.

Frederick, J. E., and D. Lubin, The budget of biologically active ultraviolet radiation in the Earth-atmosphere system, *J. Geophys. Res.*, *93*, 3825–3832, 1988.

Frederick, J. E., and H. E. Snell, Ultraviolet radiation levels during the Antarctic spring, *Science*, *241*, 438–439, 1988.

Garrison, D. L., C. W. Sullivan, and S. F. Ackley, Sea ice microbial communities in Antarctica, *BioScience*, *36*, 243–250, 1986.

Govoni, J. W., D. A. Meese, and D. K. Perovich, Optical measurements on sea ice from the Weddell Sea, Antarctica, *Antarct. J. U.S.*, *25*, 121–122, 1990.

Gow, A. J., and W. B. Tucker III, Sea ice in the polar regions, in *Polar Oceanography, Part A: Physical Science*, edited by W. O. Smith, 406 pp., Academic, San Diego, Calif., 1990.

Gow, A. J., S. F. Ackley, W. F. Weeks, and J. W. Govoni, Physical and structural characteristics of Antarctic sea ice, *Ann. Glaciol.*, *3*, 113–117, 1982.

Gow, A. J., S. F. Ackley, K. R. Buck, and K. M. Golden, Physical and structural characteristics of Weddell Sea pack ice, *CRREL Rep. 87-14*, U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N. H., 1987.

Grenfell, T. C., The effects of ice thickness on the exchange of solar radiation over the polar oceans, *J. Glaciol.*, *22*, 305–320, 1979.

Grenfell, T. C., A theoretical model of the optical properties of sea ice in the visible and near infrared, *J. Geophys. Res.*, *88*, 9723–9735, 1983.

Grenfell, T. C., and G. A. Maykut, The optical properties of ice and snow in the Arctic basin, *J. Glaciol.*, *18*, 445–463, 1977.

Grenfell, T. C., and D. K. Perovich, Radiation absorption coefficients of polycrystalline ice from 400–1400 nm, *J. Geophys. Res.*, *86*, 7447–7450, 1981.

Krueger, A. J., R. S. Stolarski, and M. R. Schoeberl, Formation of the 1988 Antarctic ozone hole, *Geophys. Res. Lett.*, *16*, 381–384, 1989.

Lange, M. A., and H. Eicken, The sea ice thickness distribution in the northwestern Weddell Sea, *J. Geophys. Res.*, *96*, 4821–4837, 1991.

Lubin, D., and J. E. Frederick, Measurements of enhanced springtime ultraviolet radiation at Palmer Station, Antarctica, *Geophys. Res. Lett.*, *16*, 783–785, 1989.

Lubin, D., and J. E. Frederick, Column ozone measurements from Palmer Station, Antarctica: Variations during the austral springs of 1988 and 1989, *J. Geophys. Res.*, *95*, 13,883–13,889, 1990.

Lubin, D., J. E. Frederick, and A. J. Krueger, The ultraviolet radiation environment of Antarctica: McMurdo Station during September-October 1987, *J. Geophys. Res.*, *94*, 8491–8496, 1989.

Lubin, D., B. G. Mitchell, J. E. Frederick, A. D. Alberts, C. R. Booth, T. Lucas, and D. Neuschuler, A contribution toward understanding the biospherical significance of Antarctic ozone depletion, *J. Geophys. Res.*, *97*, 7817–7828, 1992.

Madronich, S., Implications of recent total atmospheric ozone measurements for biologically active ultraviolet radiation reaching the Earth's surface, *Geophys. Res. Lett.*, *19*, 37–40, 1992.

McKenzie, R. L., W. A. Matthews, and P. V. Johnston, The relationship between erythemal UV and ozone, derived from spectral irradiance measurements, *Geophys. Res. Lett.*, *18*, 2269–2272, 1991.

Mitchell, B. G., Action spectra of ultraviolet photoinhibition of Antarctic phytoplankton and a model of spectral diffuse attenuation coefficients, in *Response of Marine Phytoplankton to Natural Variations in UV-B Flux*, edited by G. Mitchell, I. Sobolev, and O. Holm-Hansen, Chemical Manufacturers Association, Washington, D. C., 1990.

Palmisano, A. C., and C. W. Sullivan, Sea ice microbial communities (SIMCO), I, Distribution, abundance and primary production of ice microalgae in McMurdo Sound, Antarctica in 1980, *Polar Biol.*, *2*, 171, 1983.

Perovich, D. K., Theoretical estimates of light reflection and transmission by spatially complex and temporally varying sea ice covers, *J. Geophys. Res.*, *95*, 9557–9567, 1990.

Perovich, D. K., and J. W. Govoni, Absorption coefficients of ice from 250 to 400 nm, *Geophys. Res. Lett.*, *18*, 1233–1235, 1991.

Perovich, D. K., and T. C. Grenfell, Laboratory studies of the optical properties of young sea ice, *J. Glaciol.*, *27*, 331–346, 1981.

Schoeberl, M. R., R. S. Stolarski, and A. J. Krueger, The 1988 Antarctic ozone depletion: Comparison with previous year depletions, *Geophys. Res. Lett.*, *16*, 377–380, 1989.

Setlow, R. B., The wavelengths in sunlight effective in producing skin cancer: A theoretical analysis, *Proc. Natl. Acad. Sci. U.S.A.*, *71*, 3363–3366, 1974.

Smith, R. C., Ozone, middle ultraviolet radiation and the aquatic environment, *Photochem. Photobiol.*, *50*, 459–468, 1989.

Smith, R. C., and K. S. Baker, Optical properties of the clearest natural waters (200–800 nm), *Appl. Opt.*, *20*, 177–184, 1981.

Smith, R. C., Wan Z., and K. S. Baker, Ozone depletion in Antarctica: Modeling its effect on solar UV irradiance under clear-sky conditions, *J. Geophys. Res.*, *97*, 7383–7397, 1992*a*.

Smith, R. C., et al., Ozone depletion: Ultraviolet radiation and

phytoplankton biology in Antarctic waters, *Science*, *255*, 952–959, 1992*b*.
Solomon, S., The mystery of the ozone "hole," *Rev. Geophys.*, *26*, 131–148, 1988.
Stamnes, K., J. Slusser, and M. Bowen, Biologically effective ultraviolet radiation, total ozone abundance, and cloud optical depth at McMurdo Station, Antarctica, *Geophys. Res. Lett.*, *17*, 2181–2184, 1990.
Trodahl, H. J., and R. G. Buckley, Ultraviolet levels under sea ice during the Antarctic spring, *Science*, *245*, 194–195, 1989.
Trodahl, H. J., and R. G. Buckley, Enhanced ultraviolet transmission of Antarctic sea ice during the austral spring, *Geophys. Res. Lett.*, *17*, 2177–2179, 1990.
Tsay, S., and K. Stamnes, Ultraviolet radiation in the Arctic: The impact of potential ozone depletions and cloud effects, *J. Geophys. Res.*, *97*, 7829–7840, 1992.
Wadhams, P., M. A. Lange, and S. F. Ackley, The ice thickness distribution across the Atlantic sector of the Antarctic ocean in midwinter, *J. Geophys. Res.*, *92*, 14,535–14,552, 1987.

D. K. Perovich, U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755.

(Received May 6, 1993;
revised September 10, 1993;
accepted August 17, 1993.)